Constituent Quarks:
The Beginning of the End

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- QCD - developed in two phases:

  - Discovery of quarks

  - Specification of their interactions

- Arose from two very different traditions

  - Rutherford-Bohr

  - Einstein

- Discovery of radioactivity: Henri Becquerel (1896)

Figure 1: Becquerel's photographic plate fogged by exposure to radiation from uranium salts. The shadow of a metal Maltese Cross placed between the plate and the uranium salts is visible.

- Rutherford at Cambridge (1899): α and β

- Rutherford & Soddy at McGill (1903): "disintegration theory" of radioactivity radioactivity an atomic - not molecular - process

  Nobel prize in Chemistry (1908)

Figure 2: Rutherford's group at Manchester University, 1910

On a Diffuse Reflection of the α-Particles.

By H. GEIGER, Ph.D., John Harling Fellow, and E. MARSDEN, Hatfield Scholar, University of Manchester.

In the following experiments, however, conclusive evidence was found of the existence of a diffuse reflection of the α-particles. A small fraction of the α-particles falling upon a metal plate have their directions changed to such an extent that they emerge again at the side of incidence. To form an

- Impossible
- Marsden (1914): Nuclei contain protons
- Bohr (1914-1916): Rutherford plus Planck
- Heisenberg (1925, 1943, & 1944): Work only with observables.

Lone Ranger Atom Bomb Ring Spinthariscope (1947 - early 1950s)

This ring spinthariscope was known as the Lone Ranger Atom Bomb Ring and advertised as a "seething scientific creation." The Lone Ranger was more closely associated with silver bullets than atomic bombs but that's what it was called. When the red base (which served as a "secret message compartment") was taken off, and after a suitable period of time for dark adaptation, you could look through a small plastic lens at scintillations caused by polonium alpha particles striking a zinc sulfide screen.

Distributed by Kix Cereals (15 cents plus a boxtop), the instructions stated: "You'll see brilliant flashes of light in the inky darkness inside the atom chamber. These frenzied vivid flashes are caused by the released energy of atoms. PERFECTLY SAFE - We guarantee you can wear the KIX Atomic "Bomb" Ring with complete safety. The atomic materials inside the ring are harmless."

The following advertisement was appearing in newspapers in early 1947.

Are Mesons Elementary Particles?

E. FERMI AND C. N. YANG*

Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received August 24, 1949)

The hypothesis that π-mesons may be composite particles formed by the association of a nucleon with an anti-nucleon is discussed. From an extremely crude discussion of the model it appears that such a meson would have in most respects properties similar to those of the meson of the Yukawa theory.

I. INTRODUCTION

IN recent years several new particles have been discovered which are currently assumed to be "elementary," that is, essentially, structureless. The probability that all such particles should be really elementary becomes less and less as their number increases.

It is by no means certain that nucleons, mesons, electrons, neutrinos are all elementary particles and it could be that at least some of the failures of the present theories may be due to disregarding the possibility that some of them may have a complex structure. Unfortunately, we have no clue to decide whether this is true, much less to find out what particles are simple and what particles are complex. In what follows we will try to work out in some detail a special example more as an illustration of a possible program of the theory of particles, than in the hope that what we suggest may actually correspond to reality.

We propose to discuss the hypothesis that the π-meson may not be elementary, but may be a composite particle formed by the association of a nucleon and an anti-nucleon. The first assumption will be, therefore, that both an anti-proton and an anti-neutron exist, having the same relationship to the proton and the neutron, as the electron to the positron. Although this is an assumption that goes beyond what is known experimentally, we do not view it as a very revolutionary one. We must assume, further, that between a nucleon and an anti-nucleon strong attractive forces exist, capable of binding the two particles together.

We assume that the π-meson is a pair of nucleon and anti-nucleon bound in this way. Since the mass of the π-meson is much smaller than twice the mass of a nucleon, it is necessary to assume that the binding energy is so great that its mass equivalent is equal to the difference between twice the mass of the nucleon and the mass of the meson.

According to this view the positive meson would be the association of a proton and an anti-neutron and the negative meson would be the association of an anti-proton and a neutron. As a model of a neutral meson one could take either a pair of a neutron and an anti-neutron, or of a proton and an anti-proton.

It would be difficult to set up a not too complicated scheme of forces between a nucleon and an anti-nucleon, without about equally strong forces between two ordinary nucleons. These last forces, however, would be quite different from the ordinary nuclear forces, because they would have much greater energy and much shorter range. The reason why no experimental indication of them has been observed for ordinary nucleons may be explained by the assumption that the forces could be attractive between a nucleon and an anti-nucleon and repulsive between two ordinary nucleons. If this is the case, no bound system of two ordinary nucleons would result out of this particular type of interaction. Because of the short range very little would be noticed of such forces even in scattering phenomena.

Ordinary nuclear forces from the point of view of this theory will be discussed below.

Unfortunately we have not succeeded in working out a satisfactory relativistically invariant theory of nucleons among which such attractive forces act. For this reason all the conclusion that will be presented will be

* Now at the Institute for Advanced Study, Princeton, New Jersey.

- M. Gell-Mann & E.P. Rosenbaum, "Elementary Particles," *Scientific American*, July 1957, 72-86: 19 in number

  M. Gell-Mann & A.H. Rosenfeld, "Hyperons and Heavy Mesons," *Ann. Rev. Nucl. Sci*, 1957, 407-478:

Point particles

Spin 1/2 leptons	
Particle	Mass
e^-	1
μ^-	206.7
ν	0

Spin 1 photon	
Particle	Mass
γ	0

Extended particles (strongly interacting)

Spin 1/2 baryons		
Multiplet	Particle	Mass (m_e)
Ξ	Ξ^0	?
	Ξ^{-1}	2585
Σ	Σ^{-1}	2341
	Σ^+	2325
	Σ^0	2324
Λ	Λ	2182
N	n	1838.6
	p	1836.1

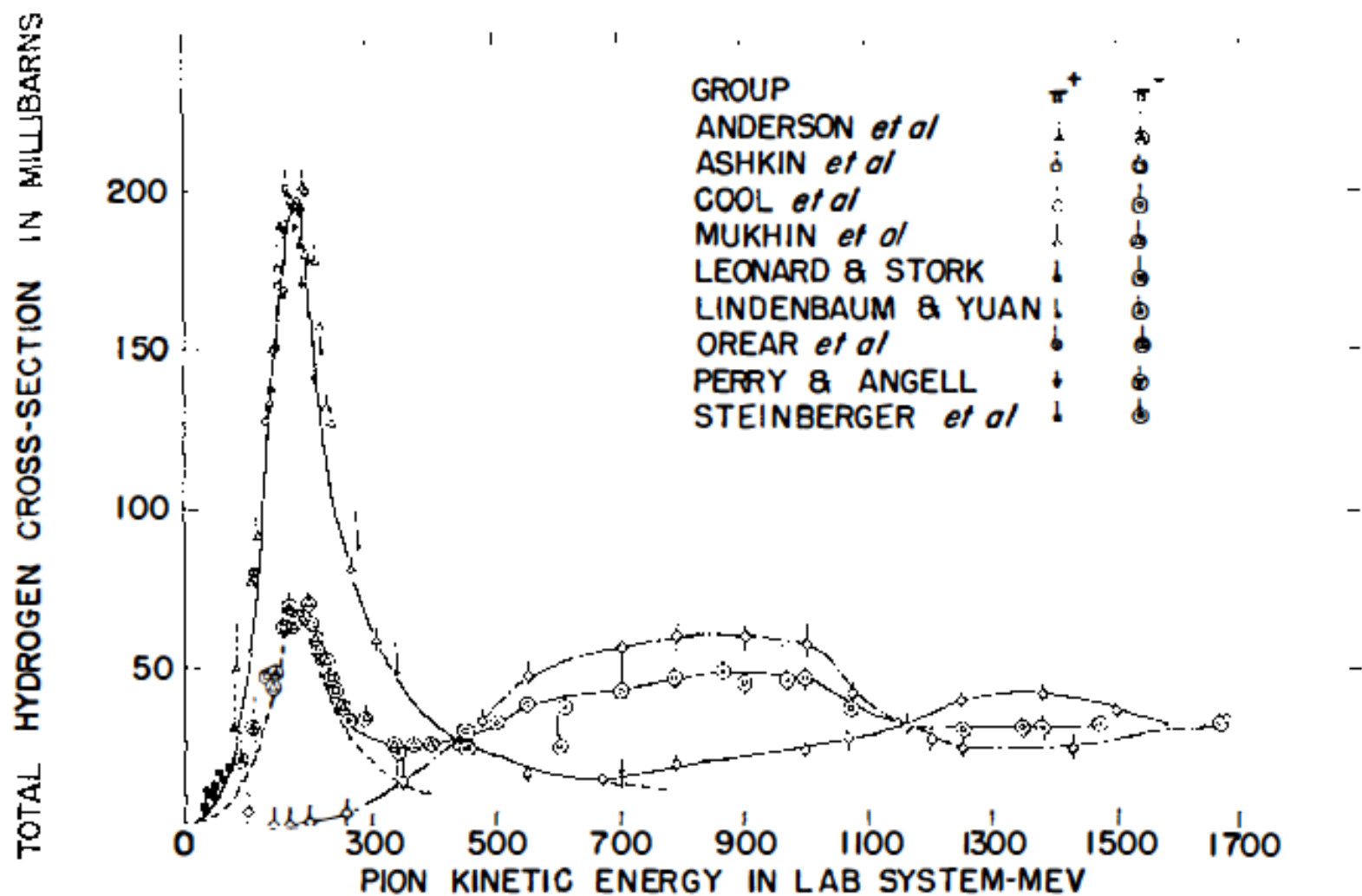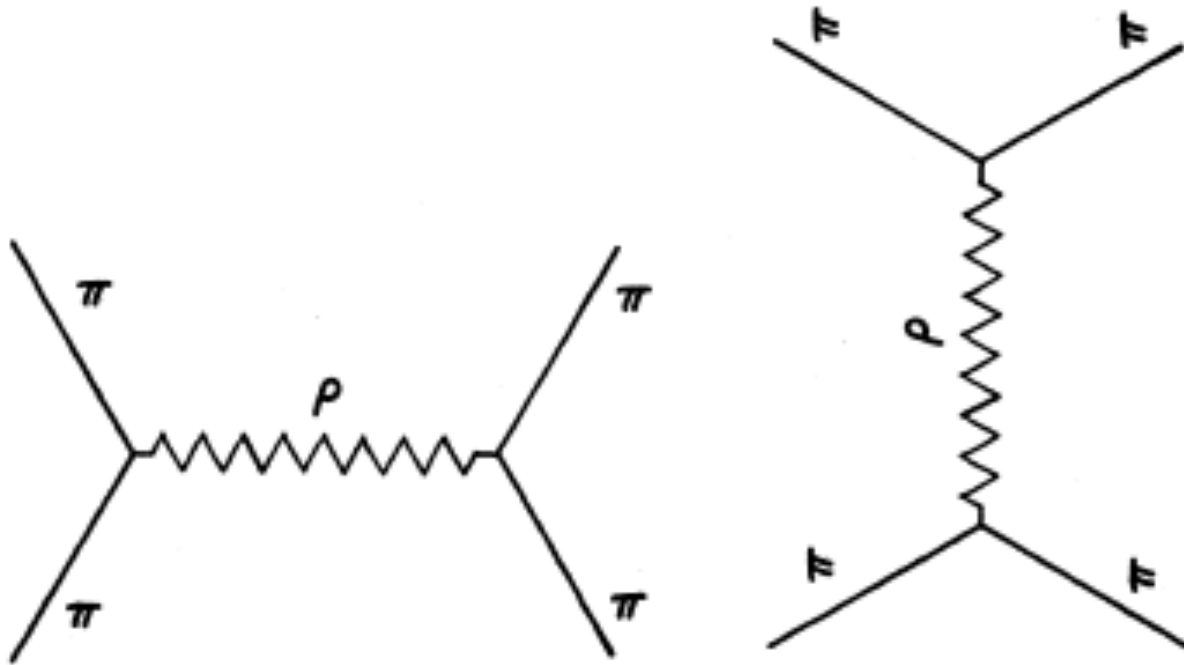| Spin 0 mesons		
Multiplet	Particle	Mass
π	π^+	273.2
	π^{-1}	273.2
	π^0	264.2
K	K^+	966.5
	K^-	966.5
	K^0_1	965
	K^0_2	965

− No resonances mentioned!

FIG. 3. A plot of $\pi^{\pm} + p$ total cross-sections as a function of energy, using in general

- Caltech:

  - My thesis: A test of time reversal symmetry $K^+ \rightarrow \pi^0 + \mu^+ + \nu$.

  - Mexico!

  - Murray?

- Every Thursday at 1:30 PM during 1962-63

- Theoretical physics
  - Axiomatic field theory
  - Theory related to belief (Chew, June 1961):

    "I believe the conventional association of fields with strongly inter-acting particles to be empty. ... field theory..., like an old soldier, is destined not to die but just fade away."

  - Theory related to experiment:
    * Particle classification (no dynamics)

∗ Dynamics - bootstrap (no classification)

The ρ bootstrap, F. Zachariasen, *Phys. Rev. Lett.* **7**, 112 (1961)

● Experimental physics

  − More particles:

    ∗ A 4th lepton (ν)

    ∗ An 8th spin 0 meson (η)

    ∗ Many more resonances: RMP March 1963, ρ, ω, K^*, $\cdots$ (26 meson resonances listed)

● One Thursday afternoon:

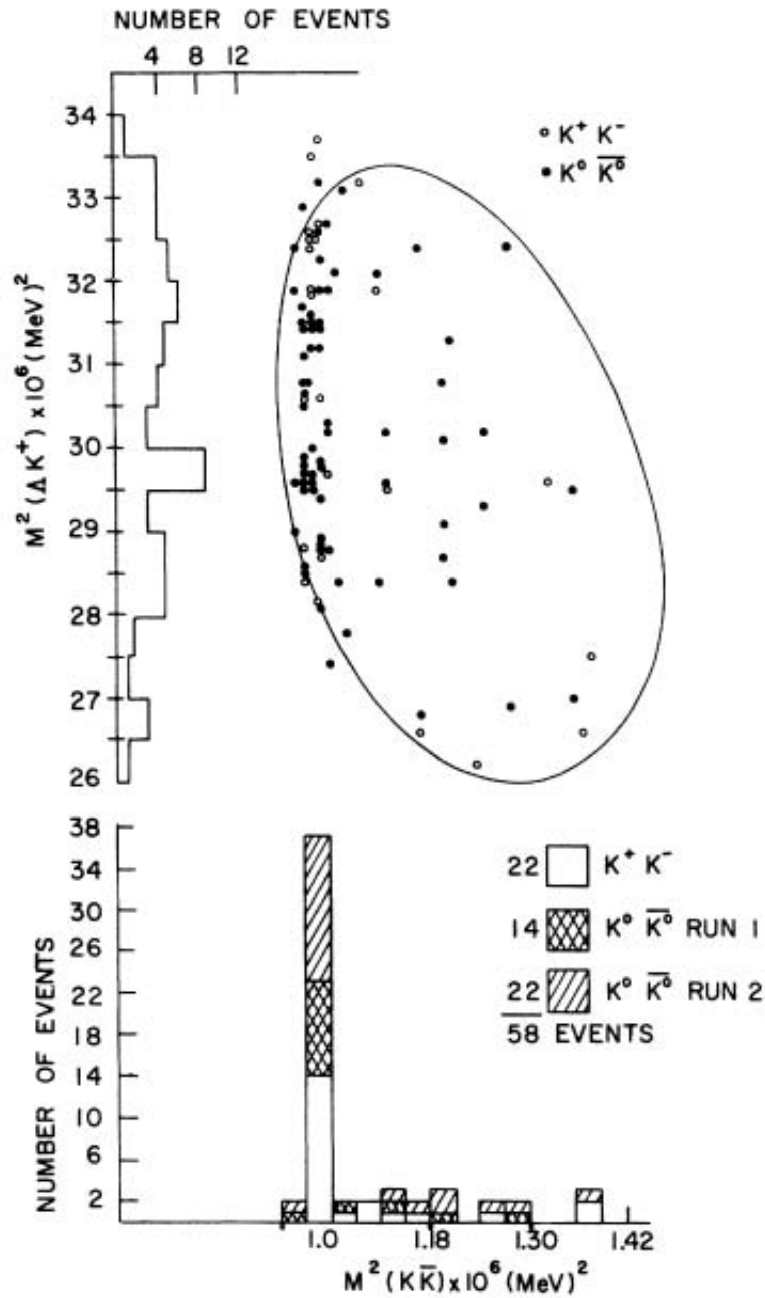P.L. Connolly, et al., "Existence and Properties of the ϕ Meson", *Phys. Rev. Lett.* **10**, 371 (1963):

FIG. 1. Dalitz plot for the reaction $K^- + p \rightarrow \Lambda + K + \bar{K}$. The effective-mass distribution for $K\bar{K}$ and for ΛK^+ are projected on the abscissa and ordinate (see reference 7).
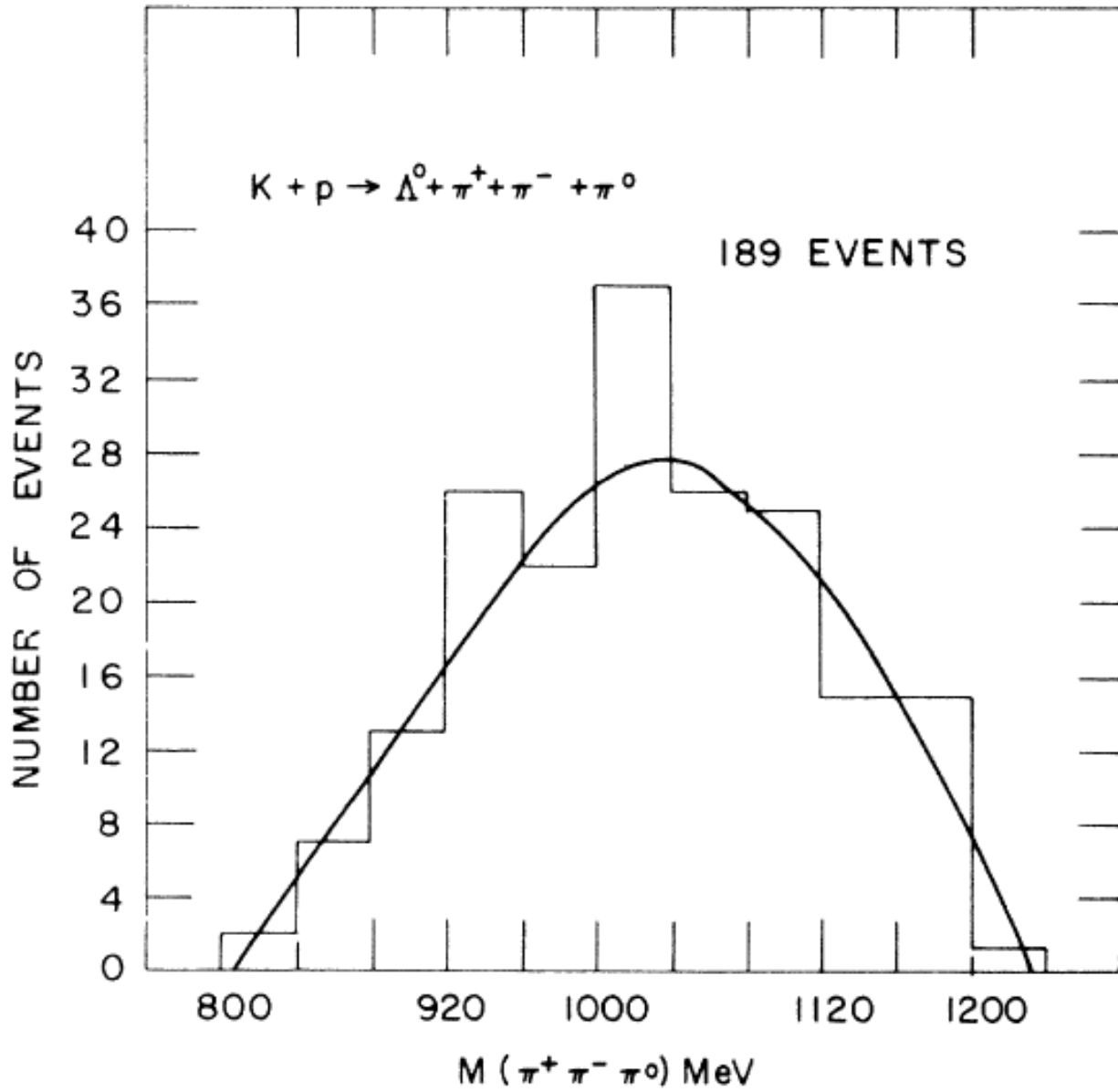
$$\phi \rightarrow K\bar{K}$$

FIG. 4. The $M(\pi^+\pi^-\pi^0)$ distribution from the reaction $K^- + p \rightarrow \Lambda + \pi^+ + \pi^- + \pi^0$ after removing Y_1^* production events (see text).

$$\phi \not\rightarrow \rho + \pi$$

$$\frac{\Gamma_{K\bar{K}}}{\Gamma_{\rho\pi}} \sim \left(\frac{p_{K\bar{K}}}{p_{\rho\pi}}\right)^3,$$

$$= \quad 0.23 \ (\text{expected}),$$
$$\geqslant \quad 35 \quad (\text{observed}).$$

"The observed rate [for $\phi \to \rho + \pi$] is lower than ... predicted values by one order of magnitude; however the above estimates are uncertain by at least this amount so that this discrepancy need not be disconcerting."
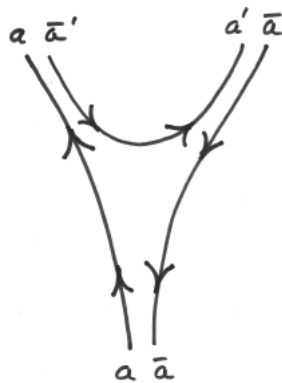
$-$ Feynman:

- Assume hadrons have constituents called aces:

$$[\,(p_0,\ n_0),\ \Lambda_0\,]\ \ \&\ \ [\,(\bar{p}_0,\ \bar{n}_0),\ \bar{\Lambda}_0\,]$$

Vector mesons as "deuces", CERN report TH-401, January 1964

- A rule for *dynamics*:

Meson decay: a is an ace, $\bar{a}$ an antiace.

   − Implies $\phi \not\to \rho + \pi$

More specifically:

- Hadrons have *point* constituents

- Lepton ↔ ace correspondance

- Unknown number: represented by regular polygons of increasing size

- Origin of SU(3) symmetry

- Beyond SU(3) symmetry:

  - Restricted representations, quantum numbers:

    * Baryons only in 1,8,10;

      mesons only in 1,8, and 9

    * $L = 0$ baryons: $(8, J^P = \frac{1}{2}^+)$ & $(10, \frac{3}{2}^+)$;

      $L = 0$ mesons: $J^{PC} = 0^{-+}$ and 1^{--}.

    * $0^{--}; 0^{+-}, 1^{-+} \cdots$ forbidden for any L

  - Symmetries broken by ace mass splittings

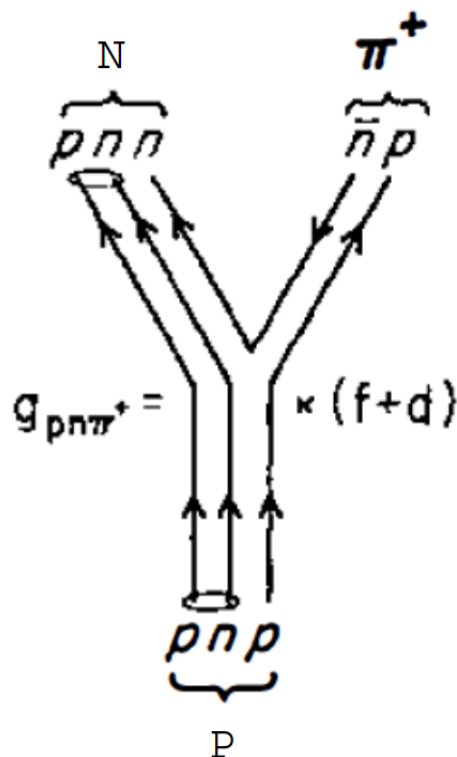   * SU(3): $m(p_0) = m(n_0) < m(\Lambda_0)$
    * SU(2): $m(p_0) < m(n_0)$

FIG. 3

Hadrons as "treys", CERN report TH-412, February 1964

– *Rule #1: Aces, not hadrons, interact.*

∗ Strong interactions: "Zweig's rule" (what's allowed!)

Graphical representation of the meson-baryon coupling.
The "little loop" encloses antisymmetrized aces.
The subscript "0" on aces is suppressed.

∗ Electromagnetic and weak interactions:

$$a \rightarrow a + \gamma$$
$$a \rightarrow a' + e^- + \nu$$

– Rule #2: Mass = Constituent masses + pairwise energies of interaction,
$$|\Delta m| > |\Delta E|.$$

* Mesons:

$$m(D_\alpha^\beta) = m(\alpha) + m(\beta) - E_\alpha^\beta$$

* Baryons:

$$m(T_{\alpha\beta\gamma}^8) = m(\alpha) + m(\beta) + m(\gamma) - E_{\alpha\beta.}^8 - E_{\alpha.\gamma}^8 - E_{.\beta\gamma}^8$$

No potential function assumed.

Not the naive quark model!

- Would you have believed?

  - SU(3) symmetry breaking:
    $$m(a_1) = m(a_2) < m(a_3)$$

    Hierarchy of baryon relations, e.g., $\frac{1}{2}^+$ octet:

    * $E^8_{\alpha\beta.} \approx E^8_{\gamma\delta.} \cdots$

      $\cdot \; m(N) < m(\Lambda) \approx m(\Sigma) < m(\Xi)$

          939   1115   1193   1316

      $\cdot \; \frac{1}{2}[m(\Xi) + m(N)] \approx \frac{1}{2}[m(\Lambda) + m(\Sigma)]$

                1127   1154

    * $\frac{1}{2}(E^8_{33.} + E^8_{\alpha\beta.}) \approx E^8_{3\alpha.} \approx E^8_{3\beta.}, \alpha, \beta = 1, 2$

      $\cdot \; \frac{1}{2}[m(\Xi) + m(N)] \approx \frac{1}{4}[3m(\Lambda) + m(\Sigma)]$

                1127   1134

      (Gell-Mann Okubo mass formula)

Hierarchy of meson relations, e.g.,
$J^{PC} = 1^{--}$ nonet:

$* \; E_\alpha^\beta \approx E_\gamma^\delta \cdots ,$

$\quad \cdot \; m(\rho) \approx m(\omega) \; < \; m(K^*) \; < \; m(\phi)$

$\qquad 750 \qquad 784 \qquad\quad 888 \qquad\quad 1018$

$* \; \frac{1}{2}(E_3^3 + E_\alpha^\beta) \approx E_3^\beta \approx E_\alpha^3 , \quad \alpha, \beta = 1, 2$

$\quad \cdot \; m^2(\phi) \approx 2m^2(K^*) - m^2(\rho)$

$\qquad (1018)^2 \qquad\qquad (1007)^2$

$- \mathrm{SU}(2)$ breaking:
$$m(a_1) < m(a_2)$$

Hierarchy of baryon relations, e.g., $\frac{1}{2}^{+}$ octet:

$*$ $E^8_{\alpha\beta.} \approx E^8_{\alpha'\beta'.}$ $\cdots$

$\cdot$ $m(p) < m(n)$
  938   939

$\cdot$ $m(\Sigma^{+}) < m(\Sigma^{0}) < m(\Sigma^{-})$
  1190   1193   1196

$\cdot$ $m(\Xi^{0}) < m(\Xi^{-})$
  1315   1321

$*$ $\frac{1}{2}(E^8_{11.} + E^8_{22.}) \approx E^8_{12.}$, $\cdots$

$\cdot$ $\frac{1}{2}[m(\Sigma^{+}) + m(\Sigma^{-})] \approx m(\Sigma^{0})]$
  1193.4 $\pm$ 0.3   1193.2 $\pm$ 0.7

$*$ No interaction energy assumptions

$\cdot$ $\boxed{m(n) - m(p) + m(\Xi^{-}) - m(\Xi^{0}) = m(\Sigma^{-}) - m(\Sigma^{+})}$

  7.3 $\pm$ 1.3   8.3 $\pm$ 0.5

  $\{8.14 \pm 0.21\}$ $\{8.08 \pm 0.08\}$

  $\{\Delta = 0.06 \pm 0.22\}$

– Additional relations for 0^{-+} meson octet and baryon $\frac{3}{2}^+$ decuplet

– Cross multiplet relations ($\Delta m > \Delta E$)

$\qquad * \; m(\Xi^*) - m(\Sigma^*) \approx m(\Xi) - m(\Sigma)$
$\qquad \qquad \quad 145 \qquad \qquad \qquad 130$

$\qquad * \; m^2(K^*) - m^2(\rho) \approx m^2(K) - m^2(\pi)$
$\qquad \qquad \quad 0.22 \; \text{Gev}^2 \qquad \qquad 0.22 \; \text{Gev}^2$

$\qquad * \; m(N) < m(\Lambda) \Rightarrow m(\rho) < m(K^*)$

– Other baryons & mesons with $L \neq 0 \; (\vec{L} \cdot \vec{S})$

– Overfitting?

$\quad [\text{QCD} \Rightarrow ?]$

– Not as easy as it looks

$\qquad * \; 26 \Rightarrow 7$, exotics

$\qquad * \;$ An earlier Thursday afternoon

- **What did people think?**

  – GZ: Duck test

  – MGM:

    ∗ "Concrete quark model"

    ∗ Five years after the deep inelastic scattering experiments at SLAC (partons) "Quarks," *Acta Physica Austriaca, Suppl. IX*, 733-761 (1972)

    > "In these lectures I want to speak about at least two interpretations of the concept of quarks for hadrons and, the possible relations between them.

    > First I want to talk about quarks as 'constituent quarks'. These were used especially by G. Zweig (1964) who referred to them as aces. ...

    > The whole idea is that hadrons act as if they are made up of quarks, but the quarks do not have to be real. If we use the quark statistics described above, we see that it would be hard to make the quarks real ...

There is a second use of quarks, as so-called 'current quarks' which is quite different from their use as constituent quarks ...

If quarks are only fictitious there are certain defects and virtues. The main defect would be that we never experimentally discover real ones and thus will never have a quarkonics industry. The virtue is that then there are no basic constituents for hadrons — hadrons act as if they were made up of quarks but no quarks exist - and, therefore, there is no reason for a distinction between the quark and bootstrap picture: they can be just two different descriptions of the same system, like wave mechanics and matrix mechanics."

– RPF:

* Current quarks?

* Constituent aces, big problem!

* The correct theory should not allow one to say which particles are elementary.

* "Have I missed anything Zweig?"

Problems with acceptance:

– Aces impossible according to the spin-statistics theorem.

  ∗ Rutherford's atom & Bohr's orbits

  ∗ Wegener's continental drift

– Aces impossible according to current dogma:

  1. Aces incompatible with nuclear democracy,

  2. The rules for aces incompatible with Heisenberg's observability requirement.

  ∗ Copernicus's view of the solar system

Acceptance criteria for ace constituents:

Bayes Theorem:

$$P(A) << 1, \quad P(E|A) \approx 1.$$

$$P(A|E) \approx \frac{1}{1+\lambda},$$

$$\lambda \equiv \frac{P(E|\overline{A})}{P(A)}.$$

Acceptance when $P(E|\overline{A}) << P(A)$.

− Einstein tradition: $P(E|\overline{A}) >> P(A)$:
− Rutherford-Bohr tradition: $P(E|\overline{A}) << P(A)$

When did acceptance come?

− Pauling
− Dalitz
− Feynman
− Deep inelastic scattering
− ψ/J

Invention or discovery?

- Current quarks invented (Einstein tradition)

- Constituent quarks (aces) discovered (Rutherford-Bohr tradition)

There are, however, many unanswered questions. Are aces particles ? If so, what are their interactions ? Do aces bind to form only deuces and treys ? What is the particle (or particles) that is responsible for binding the aces ? Why must one work with masses for the baryons and mass squares for the mesons ? And more generally, why does so simple a model yield such a good approximation to nature ?

there is also the outside chance that the model is a closer approximation to nature than we may think, and that fractionally charged aces abound within us.

Conclusion, CERN report TH-412, February 1964